Analysis of End-to-End Delay Characteristics for Various Packets in IEC 61850 Substation Communications System

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Abstract— **Substation plays an important role in power system communications for safe and reliable operation of entire power networks. Substation communication networks are connected with various substation intelligent electronic devices (IEDs), which is substation systems lifeblood and the system availability is decided by its real-time performance. International Electro-technical Commission (IEC) has been developed the standards based on object-oriented technologies for substation automation. IEC 61850 protocol has been applied widely in substation communication applications. It presents new challenges to real-time performance simulation and testing of protective relays. In this paper, an optimized network engineering tool (OPNET) or Riverbed modeler simulation tool/ software has been used for the modeling of IED in substation level network. Based on the simulation results, different types of data stream have been discussed, such as, periodic data stream, random data stream and burst data steam. The typical studies using these models, to construct substation automation system (SAS) network on the OPNET modeler or Riverbed modeler was made to reveal the impact of each affecting parameter or factor to the real-time performance of substation communications system, which is also incorporated in this report.**

Index Terms— IEC 61850, OPNET or Riverbed Modeler, Power system simulation, Real-time, Substation automation system (SAS), Transmission delay.

I. Introduction

Substation intelligent electronic devices (IEDs) are transmitted data through the data communications network. Once the data packets transfer has been delayed and has not been reached to the target devices within the predetermined period of time, which may lead to extremely serious consequences, and endanger the substation and even the entire grid [1-8]. The key objectives for designing any substation automation architecture are interoperability between the IEDs, satisfaction of communication performance, and extensibility of the architecture. The IEC 61850 is a global communication standard for substation automation system (SAS) defines the communication between the IEDs and not only solves the interoperation problem but also specifies other system requirements like message performance, information security in the SAS networks [6]. Substation communication network transmission packets have strict delay requirements, real-time study for the underlying communication network, in particular, the media access control (MAC) layer protocol, while ignoring the real-time upper-layer protocols [2]. The transmission protocol, network load and networking mode are the main factors affecting the real-time performance of the SAS network [3-4]. Among the transmission delay constitution factors, message packaging and parsing take up most of the time, which relates to the transmission model and protocol [5].

According to IEC 61850-5 standards, the messages transmission time requirements for the SAS network must be ensured under any operating conditions and contingencies inside the substation. Also, the dynamic performance of the SAS network must be studied during the planning stage in order to catch the network performance problems ahead of the deployment stage [6]. The modeling of communication system requires the definition of objects (such as, data objects, data sets, report control, and log control, etc.) and services provided by objects (such as, get, set, report, create, and delete, etc.).

However, the real-time data transmission of underlying network is only laid the basis for real-time performance of substation communication network, packets end-to-end real-time truly reflect the real-time performance of substation networks. Substation communications network usually use TCP/IP protocol stack as a network layer and transport layer protocol, in order to ensure openness and interoperability of systems [9]. An optimized network engineering tool (OPNET) or Riverbed modeler is used to simulate various SAS networks under diverse scenarios, allowing user to set the raw sample rate, fault time, number of faults, background traffic and other configuration parameters [10]. As part of the IEC 61850 standard special messages are also planned for a quick exchange of information between the IEDs, which is called generic object-oriented substation event (GOOSE) messaging [4, 11-13]. The network topology is critical when using the GOOSE messaging. Since the message may include protective signals, redundancy of the Ethernet Local Area Network (LAN) may be required [4, 14-16].

In this report, star network architectures have been used for the modeling of IEC 61850 and analyzed the simulated results. Different cases are: (i) According to substation communication network performance requirements, substation communication network architecture solutions are based on the IEC 61850 standard have been analyzed. The feasibility of the Ethernet substation communication networks are also been analyzed. (ii) Substation messages transmission delay and its impact factors using several methods that can improve the real-time performances are discussed. A comprehensive study of substation communication network packet transmission delay of the composition and the impact of this delay are considered. There are several ways to improve Ethernet real-time effective measures are also included. (iii) It has proposed to characterize the data stream for transmission substation communication network, create a data flow model. Using the OPNET network simulator, established an IEC 61850 based substation-level simulation model. Analyzed the real-time performances in substation level network with different bandwidths and different types of networks.

This paper is organized as follows: Introduction is in section I, substation automation system (SAS) model is in section II, simulation model setup is in section III. Section IV presents simulation results and discussion. Finally, the conclusion is presented in section V.

II. Substation Automation System (SAS) Model

A) Substation Level Structure Construction

There are three basic functions of a SAS, such as, control, monitoring and protection. Logically, substation based on IEC 61850 can be divided into three sections, such as, i) Substation level, ii) Bay level and, iii) Process level, as shown in Fig. 1. The station level device has database computers, operator workstations, remote communication interfaces; the process level device has typical I/O's, smart sensors and actuators; and the bay level device has control and protection or monitoring units, etc.

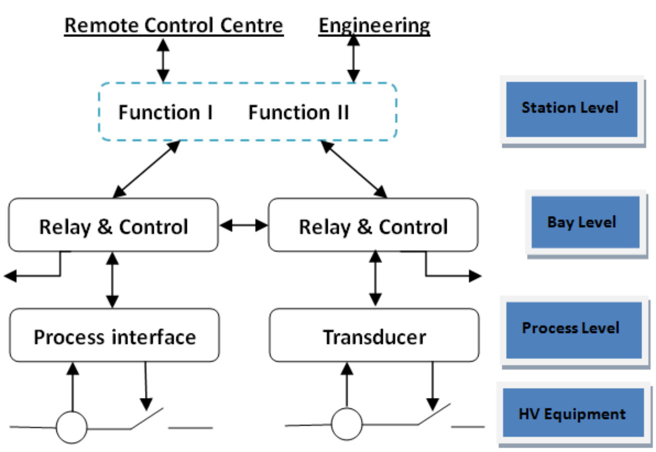

Fig. 1. Diagram of SAS hierarchy and logical interfaces.

B) Substation Level Data Flow Analysis

There are several types of data flow within a substation. Based on IEC 61850 protocols, the characteristics of the packet can be divided into seven different categories (or types) of messages, as listed in Table-I.

In terms of time domain, substation communication network data stream can be summarized in three main streams. These are namely as: i) periodic data stream, ii) random data stream, and iii) burst data stream. The periodic data stream means the regular transmission of switch state information and analogue data from bay level IEDs to station level monitoring devices during normal operation. There are huge amount of this type of data, it requires high level real-time performance, the data variation is very small, having good stability. The random data, including some short length and high real-time data packets, such as: switch operation commands, time synchronization, also include some long length and low real-time packets, such as relay protection setting value modification, wave record data transmission. The burst data stream, including data transmission of protection action and switch position changing from bay level IEDs to station level monitoring under frequent node failures and multi-faults situations. It combines large amount of data, also require a high level real-time performance.

Table-I. Message type and performance requirement in SAS network [8].

Message Type	Example Messages In PICOM	Transfer Time Range (ms)
1. Fast Message	Trigger	10 - 100
	Complex Block or Release	10 - 100
	Fast Broadcast Message	1
	Process State Changed	10 - 100
	Trip	1
2. Medium Speed Message	Process Value in r.m.s.	50 - 1000
	Request for synchrocheck, interlocking	10 - 100
	Process State	1 - 100
	External State	1 - 100
3. Low Speed Message	Measured Value or Meter Value such as Energy	100–1000
	Non-electrical Process Value (temperature)	1000 -5000
	Fault Value e.g. fault distance	0.1 - 5000
	Event/Alarm	100 - 1000
	Mode of Operation	10 - 100
	Set Point	100 - 1000
	Acknowledgement by Operator or auto.	10 - 1000
	Date and Time	100 - 1000
4. Raw Data Message	Process Value (sample voltage & current)	0.1 -10
5. File Transfer	Report such as Calculated Energy List	1000 -5000
	Mixed Fault Information	1000 -5000
	Mixed Fault Data such as Disturbance Recording	5000
	Event/Alarm List	100 - 1000
	ID Data, Setting	1000 -5000
	Diagnostic Data	5000
6. Time Synchro-nization Message	Synchronization Pulse	0.1 - 10
7. Command Message with Access Control	Command	1 – 1000

C) IEC 61850 Communication Model

Time constraint is one of the most critical issues for the transmission of sampled values. The IEC 61850 communication model provides transmission of sampled values in an organized and time controlled way, so that the combined jitter of sampling and transmission is reduced to a degree that an unambiguous allocation of the samples, times and sequence is provided. The communication model applies to the exchange of values received from multiple IED's after A/D conversion. A transmission-reception buffer structure is defined for the transmission of the sampled values.

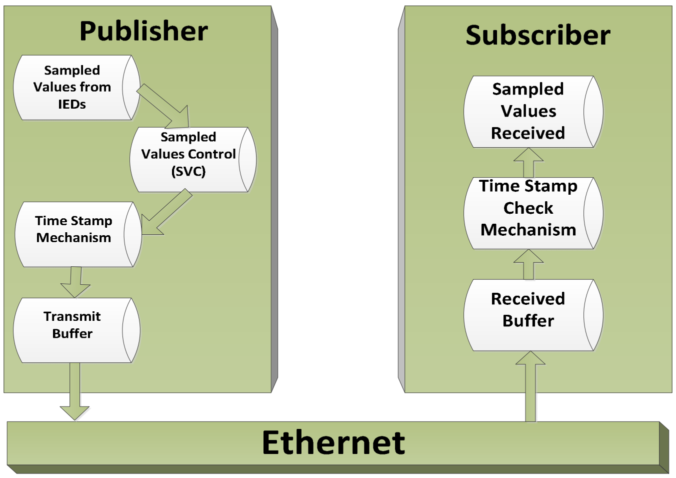

Fig. 2. IEC 61850 communications model for sampled value data.

Fig. 2 shows the IEC 61850 communications model for sampled value data via Ethernet. The communication procedure is based on a publisher /subscriber mechanism. First of all, publisher shall use the time stamp mechanism to attach time stamp for data synchronization. After that, the publisher will send the time stamped data to transmit buffer. The sampled value control block in the publisher is used to control the overall communication procedure. The sampled values from the transmit buffer are send via high speed Ethernet to subscriber. The subscriber will receive the sampled values in a receiver buffer. After that the sampled value data is sent to time stamp check mechanism to confirm the time synchronization of the received data. After that data is sent to the control and monitoring section for further data analysis.

III. Simulation Model Set Up

A) OPNET Simulation Model

IEC 61850 uses several stacks for different kinds of traffic. Fig. 3 shows the network simulation process or flow diagrams. For this modelling, a star topology has been used in a substation bus level network, the IEDs between bay level and substation level are connected together through a switch. In this model, a D2 type medium-sized distribution substation is defined as an IEC 61850. According to the data flow characteristics of the substation communication network, the OPNET modeller software is used to analysis the real-time performances of the substation level network based on IEC 61850.

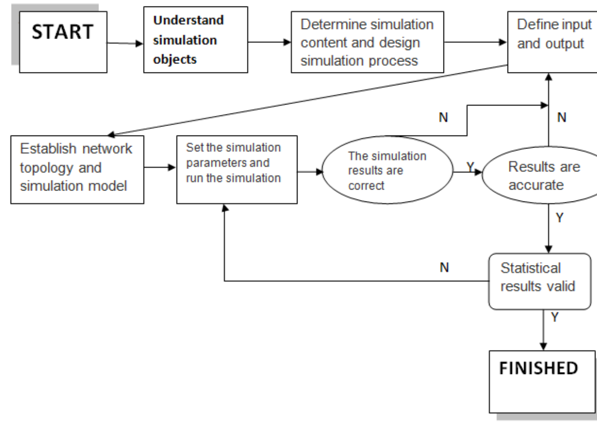

Fig. 3. Network simulation flow diagram or chat.

Fig. 4 shows the station level network simulation model by OPNET which is consists of 18 bay level IEDs, a substation monitoring host and a server. Each network node is connected with the Ethernet communication network by 10-BaseT UTP. In order to increase the reliability of the network, the substation bus is required to build a dual network redundancy. Due to the independence of the physical network and the logic network, only one network simulation is required. So, only the internal network communication has been simulated, to the exclusion of the remote communication part.

As, each logical node (LN) message mapping includes TCP/IP protocol layer, all objects and services are the base of the function model, directly use the ethernet_wkstn_adv LN model in OPNET to simulate the data communication between station level and bay level. The data model including its services is mapped to a mainstream communication stack consisting of manufacturing message specification, TCP/IP, and Ethernet; time critical messages directly to the link layer of the Ethernet.

By using the video conference service to simulate the periodic data stream and the random data stream, using the file transfer protocol (FTP) service to simulate the Bay level protection and control (P&C) IEDs to send fault recorder, protection action information and unexpected stream to substation level.

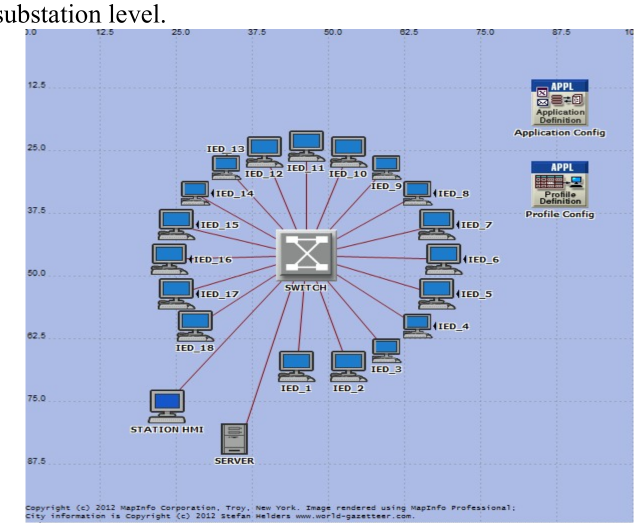

Fig. 4. Station level network simulation model by OPNET.

Application Config and profile Config have been used to configure the global parameters of the simulation model. The application Config set with application parameters, which describe the action of applications, including the size of a packet or the data sending interval e.g., profile Config is used to describe the applications involved in the same user group, also used for describing the specification of each application, such as when the simulation starts and how long it will last. During a simulation, packets sent from IEDs are received by the hub receiver object (hub_rx_0_0) and processed up the protocol stack to the application module. After processing, they are sent down the stack to the transmitter (hub_tx_0_0), then back to the IEDs [10].

B) Simulation Parameters Configuration

The worst event of the load bus has been considered as the simulation conditions, including the periodic data flow, random data flow and burst data flow. These data flows are discussed in the previous section. The specific configurations are listed as follows:

(1) *Periodic data stream:* the bay level LNs using the user datagram protocol (UDP), to send all the telesignalisation and telemetering to the host by 20 ms cycle, such as, analogue values and status information etc., and the data length is 256 bytes [10].

The main configuration parameters of the video conference are as follows:
Incoming Stream Interarrival Time (s): constant (0.02)
Outgoing Stream Interarrival Time (s): constant (0.02)
Incoming Stream, Frame Time (bytes): constant (256)
Outgoing Stream Frame Time (bytes): constant (256).

(2) *Random data stream:* The host send control command packets to bay level notes IDE1 and IED2, the message length is 128 bytes and the arrived packets obey the exponential distribution of $\lambda = 0.01$ [10].

The main configuration parameters of the video conference are as follows:
Incoming Stream Interarrival Time (s): exponential (0.01)
Outgoing Stream Interarrival Time (s): exponential (0.01)
Incoming Stream, Frame Time (bytes): constant (128)
Outgoing Stream Frame Time (bytes): constant (128)

(3) *Burst data stream:* Server nodes send the burst data stream packets to the host nodes via FTP, the arrived messages obey the Pareto distribution by the ON duration parameters [10], $k = 0.512$ ms, $\alpha = 1.1$, and the OFF duration subject to the negative exponential distribution of $1/\lambda$, the length of the data is subject to a constant distribution with 1024-byte mean value. The configuration parameters of the FTP are as follows:
Command Mix (Get / Total): 50%
Inter-request Time (s): Pareto (0.000512, 1.1)
File Size (bytes): constant (1024)

IV. Simulation Results and Discussion

This section discussed the overall performance of the star topology network; such as, sending packet sizes, sending interval and CPU utilization has been simulated, and the impact to end-to-end data caused by high-level protocol. By changing a single variable in the simulation, simply it is possible to analyse the real-time performance of the transmission system [11-13].

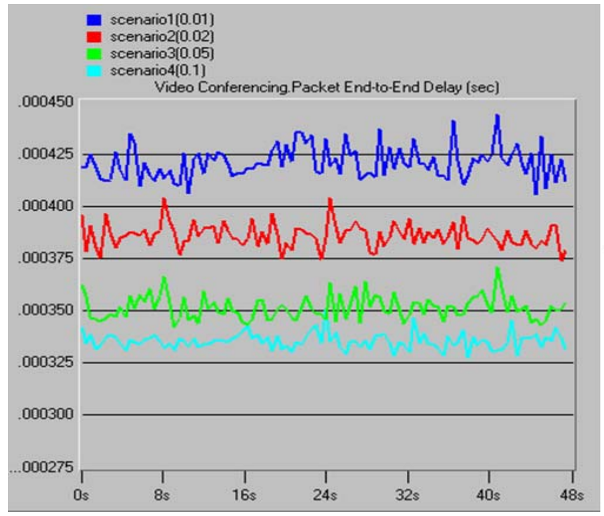

Fig. 5. Comparison of end-to-end *transmission delay* messages in different packet interval.

A comparison of end-to-end transmission delay messages in different packet interval is shown in Fig. 5. The packet interval time from top to bottom is 0.01-s, 0.02-s, 0.05-s, and 0.1-s, respectively. The rest of the configurations remain the same. The end-to-end real-time performance of the relay protection data stream is impacted by the interval of the periodic data stream. Fig. 5 shows clearly that when the packet interval is 0.01-s, the end-to-end delay in 0.425-ms fluctuation, compared when packet interval is 0.1-s, the delay fluctuation is reduced to 0.337-ms. It shows clearly that the data stream interval is smaller, the end-to-end delay time is greater and more undulate.

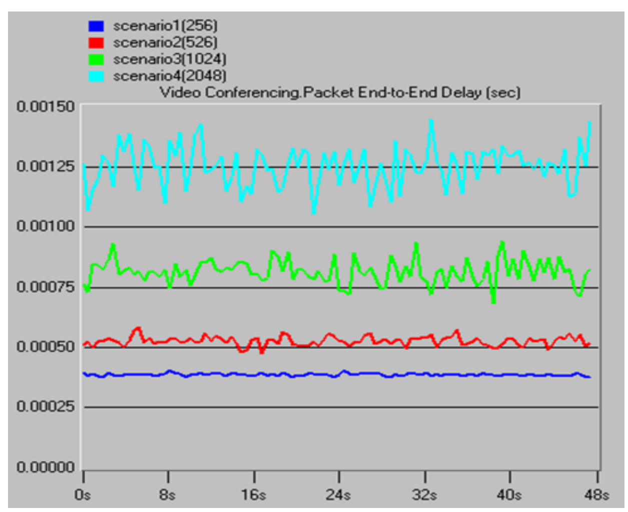

Fig. 6. Comparison of end-to-end *transmission delay* messages in different packet sizes.

Fig. 6 shows the comparison of end-to-end transmission delay messages in different packet sizes. The packet sizes from top to bottom are 256, 526, 1024, and 2048 bytes, respectively. It shows clearly that with the increase of packet sizes, the end-to-end delay time increases. When data packet size is 256 bytes, the end-to-end delay is about 0.4-ms and the delay variation is not much fluctuating (i.e., like a smooth variation or a steady condition), but when the packet size is 2048 bytes, the end-to-end delay significantly increases with huge variations. For this reason, in the actual (such as, realistic or practical) configuration, it should avoid sending a variety of data streams at the same time, as well as avoid to send too large packet sizes to meet the real-time requirements [11-13].

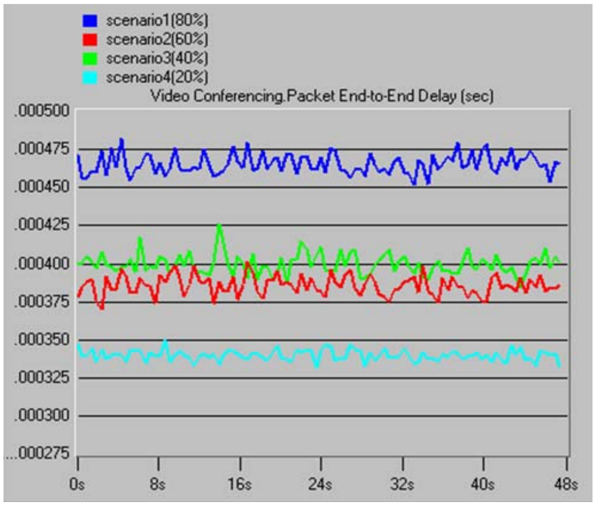

Fig. 7. Comparison of end-to-end *transmission delay* messages in different CPU background utilization.

Fig. 7 shows the comparison of end-to-end transmission delay messages in different CPU background utilization. The CPU background utilization from top to bottom are 80%, 60%, 40%, and 20%, respectively. It shows clearly that when the CPU background utilization is increasing then the delay of the protective relaying data stream is increasing. However, when the CPU background utilization is increasing, the station bus traffic is increasing, the possible conflicts to reduce real-time performances of the protective relaying end-to-end data stream, which can be solved by reducing the link background utilization or increasing the Ethernet bandwidth.

V. Conclusion

In conclusion, this paper presented the performance of IEC 61850 based substation communication systems and proposed for practical application in power industries. For practical application in industry, it should optimize the size of packets, select small or reasonable packets and avoid too large packets, and avoid to send a variety of data streams at the same time to ensure real-time and reliable data transmission. To meet the high level real-time requirements for substation protection relay data stream, with modelling of communication between bay level protection & control IEDs and station level local monitoring. The main factors affecting the delay have been concluded, such as, (i) the packet interval transmission, (ii) the packet sizes, and (iii) the utilization of CPU background. The transmission data stream should be set at high-level of protocols, high real-time requirement of the selected UDP/IP, and high reliability requirement of the selected TCP/IP for different levels. Therefore, for practical application in industry, it is recommended to consider reasonable configuration of parameters, hence the real-time data transmission will improve and ensure the normal operation of substation communication systems.

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